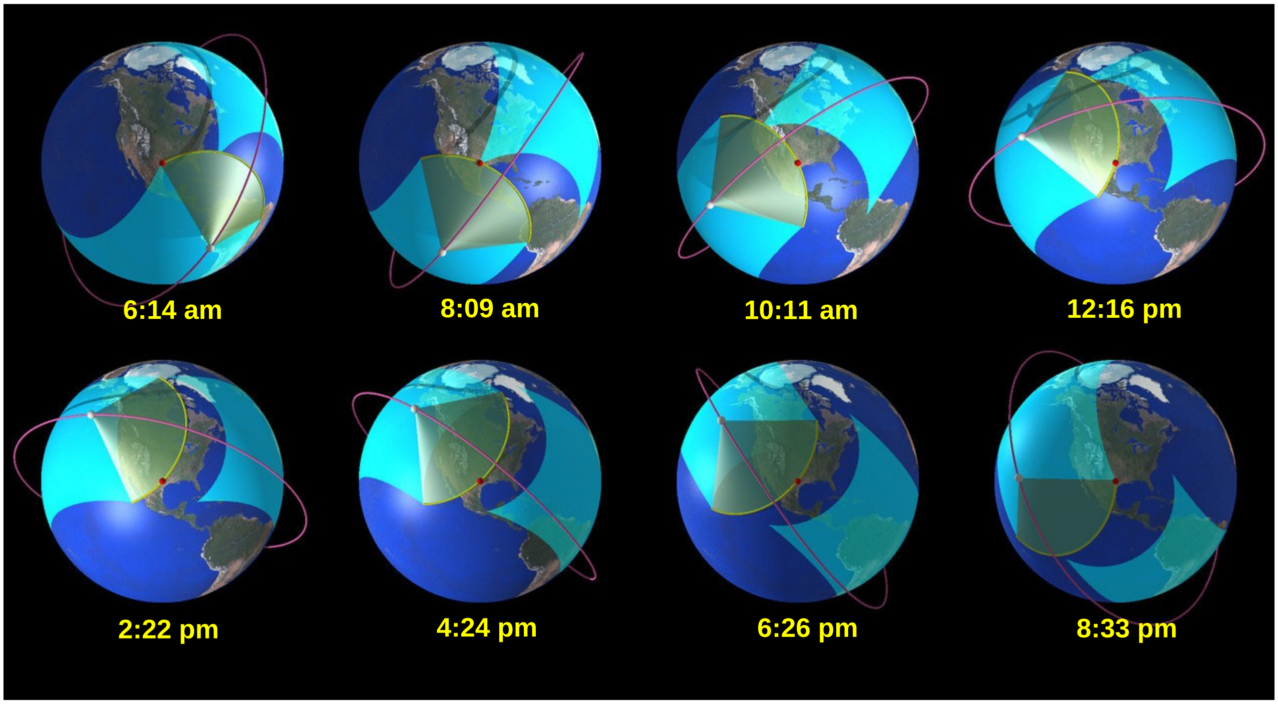
# Composition of the Atmosphere from Mid-Earth Orbit (CAMEO)

A mission concept submitted in response to the 27 January 2005 request for information by the U.S. National Research Council Decadal Study on *Earth Science and Applications from Space*




*CAMEO's overlapping coverage on successive orbits: an unprecedented combination of temporal, vertical, and horizontal resolution, and global coverage needed for atmospheric research and monitoring. The labels give local times for this example day's measurements over Houston (red dot).*

submitted 16 May 2005 by

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# Composition of the Atmosphere from Mid-Earth Orbit (CAMEO)

## 1. Summary of the Mission Concept

Although the past few decades have seen tremendous progress in our ability to globally measure atmospheric composition, major deficiencies still exist in temporal resolution of observations and measurement capability for the upper troposphere. These deficiencies have inhibited progress in atmospheric science and applications directly linked to societal needs and benefits. Important processes having time scales of less than several hours are not currently observable globally, but have major influences on (1) local air quality, (2) how regional (e.g., Asian or North American) and sub-regional (e.g., megacity) pollution affects global air quality, (3) the chemistry of $O_3$ in the upper troposphere where it has the largest effect on climate, (4) how upper tropospheric water vapor affects climate variability, (5) the performance of weather and climate models, and (6) possibly the transport of gases into the stratosphere affecting ozone stability.

CAMEO brings these processes into sharp relief by filling the observational gaps with an unprecedented combination of temporal, vertical, and horizontal resolution and global coverage for important measurements from the boundary layer to the stratopause. It provides new upper tropospheric measurements, for which the temporal resolution is especially important. CAMEO also continues critical measurements for assessing the stability of the ozone layer. The mission addresses priorities stated by four of the seven NRC Decadal Study panels:

**Human Health and Security** − by providing information on air quality and ozone layer stability;

**Climate Variability and Change** − by providing information to improve understanding of climate forcings, feedbacks, and responses; to improve predictions on a variety of time scales; and to continue climate data records;

**Weather** − by providing information that improves predictions and understanding of air quality, and that improves forecasting models and the use of assimilation in assessing problems of prediction;

**Water Resources and the Global Hydrological Cycle** − by providing information on water vapor and clouds, which is needed to improve the representation of hydrological processes in GCMs.

CAMEO uses an easily-reached 'mid-Earth' orbit (MEO, ~1000-10,000 km height) and two instruments having broad measurement swaths:

**The Scanning Microwave Limb Sounder (SMLS)** that observes thermal emission to measure many chemical species, ice cloud parameters, and temperature. SMLS measures every 50×50 km in the horizontal and 1-2 km in the vertical. It combines the proven MLS technique with a novel scanning antenna and ultra-sensitive millimeter/submillimeter radiometers in two broad spectral bands. SMLS has heritage from UARS MLS and Aura MLS.

**The TROpospheric Pollution Imager (TROPI)** that observes scattered/reflected solar ultraviolet/visible (UV/Vis) and short-wavelength infrared (SWIR) to measure columns and infer lower tropospheric $O_3$, $NO_2$, $SO_2$, CO, $H_2CO$, $CH_4$, BrO, aerosol/cloud properties, and surface UV-B flux. It measures every 20×20 km, and combines a proven instrument concept with new detector technology. It has heritage from OMI on Aura, SCIAMACHY on ENVISAT.

Fig. 1 shows coverage of these instruments in a 1500-km, 52$^o$ inclination circular orbit. This 1.9 hour period orbit is selected as a good compromise between higher orbits that are more difficult to implement and lower orbits that have poorer global coverage. The inclination, and right ascension of the ascending node, are chosen to favor measurements in the summer hemisphere (for air quality issues), to give year-round SMLS measurements to ±82$^o$ latitude on each orbit, and to have a coverage pattern that repeats annually. Further studies may yield a still more favorable orbit.

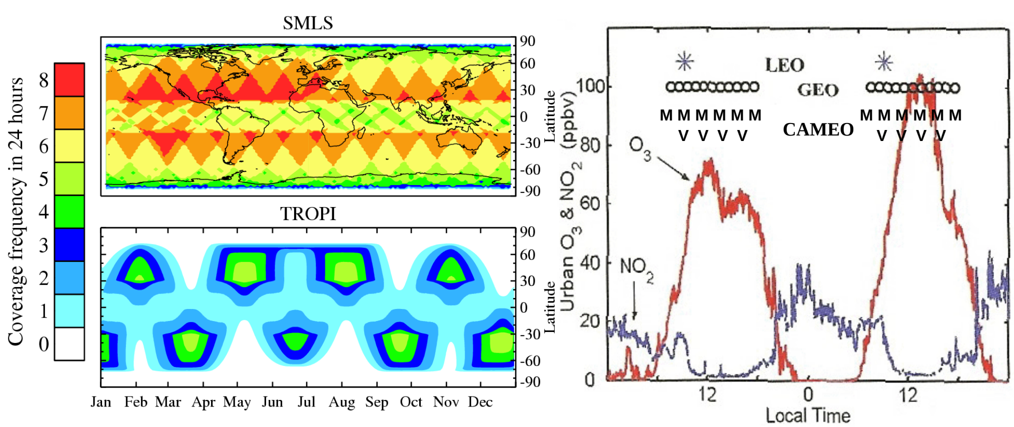



**Figure 1. Left:** CAMEO coverage frequency for a 24-hour period. **(top)** SMLS coverage for a typical day; everywhere within a given color is measured the number of times per 24-hour period indicated by that color. **(bottom)** TROPI UV/Vis coverage annual variation; all longitudes within a given color are measured that number of times per day. TROPI's SWIR, which measures CO and $CH_4$, has a narrower swath that yields ~1/2 the UV/Vis frequency. **Right:** Temporal coverage from different orbits. This is from the NRC reference document "Understanding the Effect of Environmental Factors on Human Health and Well-Being", with CAMEO added ("M" for SMLS; "V" for TROPI UV/Vis that measures, among other pollutants, $O_3$ and $NO_2$ whose diurnal variations in urban regions are plotted). CAMEO coverage shown here is for SMLS measurements at all latitudes up to ±75$^o$ (the local times of these precess), and TROPI UV/Vis coverage for all longitudes at 30-60$^o$N in Feb, May, Aug, Nov; and 30-60$^o$S in Mar, Jun, Sep, Dec. A single GEO gives good temporal coverage all the time, but for only 20% of the globe. Multiple satellites of either type can give more global coverage: completely for MEO; up to ±60$^o$ latitude for GEO.

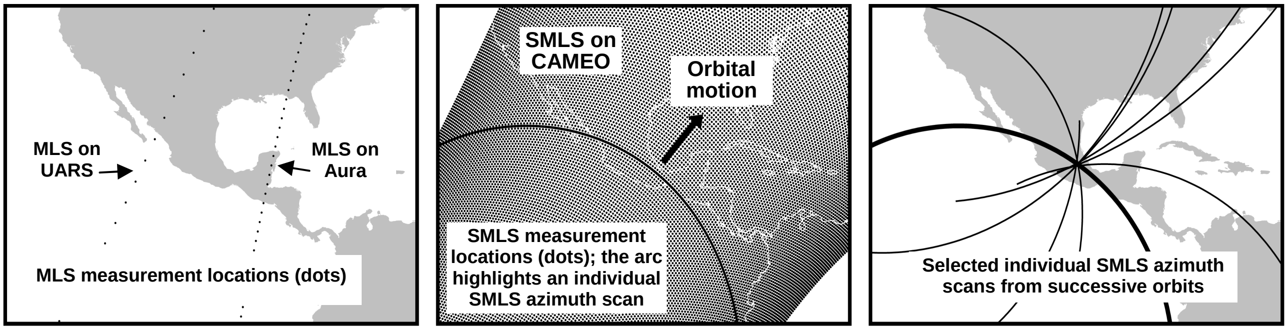



**Figure 2.** Comparing coverage from a portion of one orbit for **(left)** MLS on UARS and MLS on Aura; **(center)** SMLS on CAMEO; **(right)** individual SMLS scans from successive orbits. Only a single scan from each orbit is plotted in the right panel for clarity, but the entire region is covered by overlapping measurements on successive orbits. This illustrates how the air over Mexico City is repeatedly observed on successive orbits. The cover figure shows an example of similar coverage for Houston.

Fig. 2 shows the dramatic improvement in the coverage of SMLS over that of previous MLS instruments, and gives an example of the successive orbit overlaps that yield its temporal sampling. The SMLS field-of-view (FOV) width at the tangent point is 30 km in azimuth (horizontal, normal to the line of sight) and 0.5-1 km in vertical. Special 'limb-tracking' observations of Aura MLS have shown that 50 km horizontal resolution (or better) along the line-of-sight can be achieved with SMLS. TROPI temporal coverage is obtained similarly, through overlaps on successive orbits, but is limited to daylight. Its horizontal resolution is set by its effective 20×20 km 'pixel' width.

NOAA's Advanced Concepts Development Group is planning to use MEO for NOAA's future post-GOES-R operational system ('National Global Operational Environmental Satellite System', NGOESS) to be implemented around 2025. CAMEO will demonstrate an important new capability that could be deployed in this future operational system; the CAMEO instruments can be adapted for the NGOESS orbits being considered by NOAA.

Fig. 3 shows the CAMEO measurement suite. SMLS measures stratospheric profiles and columns with a few percent precision and accuracy, and temperature profiles with 0.1K precision and ~1K accuracy. The SMLS upper tropospheric precision is addressed later by Fig. 7. TROPI tropospheric column measurement accuracy is several percent for $CH_4$, 10-20% for $O_3$, $NO_2$ and CO, and ~50% for $CH_2O$ and $SO_2$, depending on atmospheric conditions; we anticipate this can be improved for some gases (e.g., $O_3$) by combining TROPI and SMLS data.

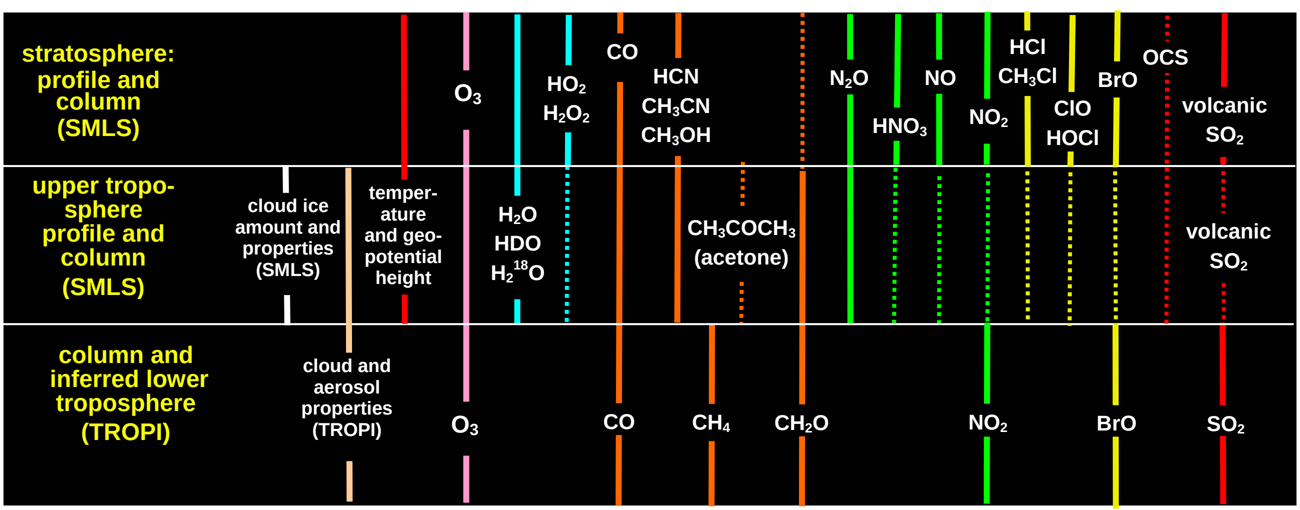



**Figure 3.** CAMEO measurements. Dotted lines are goals. Surface UV-B flux is also measured.

## 2. How the mission will help advance Earth science and applications, and provide a needed operational capability

CAMEO advances Earth science by providing an unprecedented combination of vertical, horizontal, and temporal resolution, and global coverage needed to improve our understanding of air quality, tropospheric sources and sinks, climate variability, and the predictions of weather and climate variability on various time scales. It will monitor the stability of the ozone layer. These topics are discussed further in section 4. CAMEO will be a pathfinder for future operational capabilities to monitor atmospheric chemistry, and provide information for operational predictions of air quality ("chemical weather") and weather and climate variability.

## 3. Rough estimate of the total cost

An excellent opportunity exists for international partnering on this mission: the Dutch authors of this paper are proposing TROPI to ESA in response to a recent AO. The two CAMEO instruments could either be together on the same satellite, or on separate satellites flying in formation. The total cost of the SMLS instrument, operations and data processing is in the ‘low’ category (as defined in the NRC RFI). The overall U.S. cost of an ‘SMLS-only’ mission is in the ‘medium’ category. Flying SMLS on the same satellite with TROPI could put U.S. costs into the ‘high’ category, depending upon the sharing of responsibilities/costs for the launch vehicle and satellite bus.

## 4. How the mission meets criteria given in the NRC Decadal Study Request for Information

### 4a. Provides information identified as high priority in previous study

Table 1 maps the CAMEO observations to the societal benefit area priorities as given in the International Working Group on Earth Observations (IWGEO) *Strategic Plan for the U.S. Integrated Earth Observation System* [from http://iwgeo.ssc.nasa.gov, 15 April 2005].

**Table 1**. CAMEO observations mapped to the IWGEO ‘level of importance to societal benefit areas’: H is high importance, M medium; L low. (We would also put ‘Atmospheric Profiles’ and ‘Cloud Cover’ as high for ‘Water’; ‘Radiative Flux’ as high for ‘Health’ and ‘Ecology’.)

| **CAMEO Observations** / **Societal Benefit Area**<br>**IWGEO categories are in bold**<br>*CAMEO specifics are in italics* | Weather | Disasters | Oceans | Climate | Agriculture | Health | Ecology | Water | Energy |
|---|---|---|---|---|---|---|---|---|---|
| **Atmospheric Constituents:** *$O_3$, CO, $CH_4$, $CH_2O$, $NO_2$, $SO_2$, $H_2O$, HCl, ClO, BrO, $HNO_3$, $HO_2$, NO, $N_2O$, HDO, $H_2^{18}O$, $H_2O_2$, HCN, $CH_3CN$, $CH_3OH$, $CH_3Cl$, HOCl, aerosol properties* | L | H | M | H | L | H | L | H | H |
| **Atmospheric Profiles:** *temperature, pressure, water vapor, cloud ice content and size parameter, constituents listed in line above* | H | H | L | H | L | M | L | L | L |
| **Cloud Cover:** *distribution, scattering layer pressure, ice content vertical profile, ice size parameter vertical profile* | H | M | M | H | M | L | L | L | L |
| **Total and Clear Sky Radiative Flux:** *surface UV-B flux* | H | L | M | H | H | M | M | M | H |

### 4b. CAMEO makes significant contributions to four of the seven Decadal Study Panel themes

These are listed on page 1 and discussed in the following subsections.

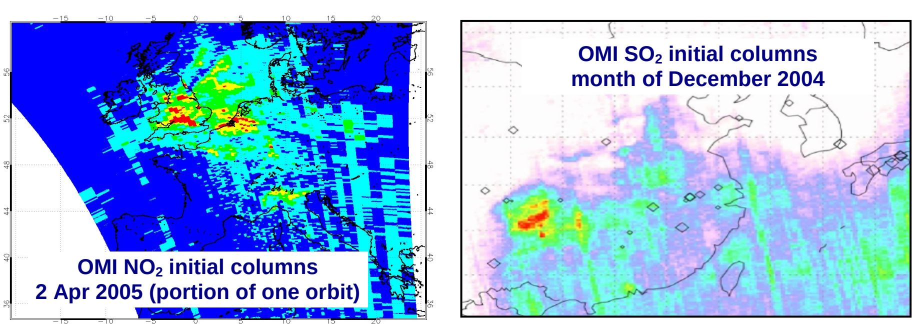
### 4c. CAMEO contributes to important scientific questions facing Earth sciences today

CAMEO contributes to the resolution of important questions in the areas of (1) air quality, (2) climate variability and change, (3) weather and climate modeling, and (4) ozone layer stability.

*Air quality*

Assessing changes in global air quality (and the causes/implications of these changes) is an important international issue. There is evidence that northern hemisphere tropospheric $O_3$ abundances have increased several-fold since pre-industrial times. This increase has been linked to industrial emissions of the $O_3$ precursors $CH_4$, CO, $NO_x$, and volatile organic compounds (VOCs), but the specific contributions are not well quantified. Through its chemical impact on OH, the $O_3$ increase may be affecting the oxidizing capacity of the atmosphere. Changes in the oxidizing capacity would have wide-ranging implications for future global air quality, aerosol formation, greenhouse radiative forcing, and stratospheric ozone layer stability. CAMEO’s multiple daily measurements of tropospheric $O_3$, $CH_4$, CO, $NO_2$, $CH_2O$ as a proxy for VOCs, and $SO_2$ (a sulfate aerosol precursor and cause of acid rain), provide the temporal resolution (see the $O_3$ and $NO_2$ plots in Fig. 1) to quantify their global/regional distributions and sources/sinks. Fig. 4 shows Aura OMI UV/Vis maps of tropospheric $NO_2$ and $SO_2$ that clearly identify source regions. TROPI provides robust measurements of lower tropospheric abundances, aided where needed (e.g., for $O_3$ and $NO_2$) by subtracting SMLS columns for the upper troposphere and stratosphere, to give surface emission inventories of these gases.

**Figure 4.** OMI measurements of **(left)** $NO_2$ over Europe and **(right)** $SO_2$ over China.



The combined resolution and global coverage of CAMEO will greatly improve our ability to assess the contributions of regional and sub-regional pollution to the global atmosphere, as well as the influence of global changes on regional pollution. How is a nation's air quality affected by pollution arising beyond its region of control? A widely-cited study [Jacob et al., *GRL*, 1999] shows how rising Asian emissions can impact air quality in the U.S. The TROPI measurements of dust, smoke, and industrial aerosols track pollution plumes on scales ranging from regional to global. Convective lofting of pollutants into the upper troposphere increases the potential for their intercontinental transport. As shown in Fig. 5, Aura's MLS has measured, with coarse resolution, enhanced abundances of upper tropospheric CO that can be traced to uplifted surface pollution from India and China. SMLS can measure vertical profiles of CO and other upper tropospheric chemicals several times per day globally every 50×50 km to provide needed information on transport of pollution.

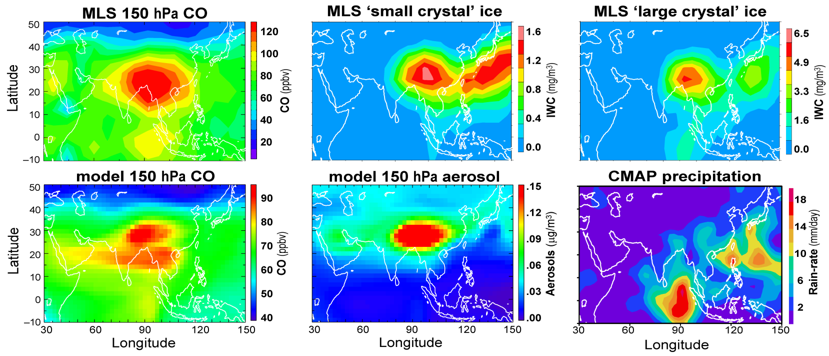



**Figure 5. Top row:** Aura MLS maps of upper tropospheric CO and cloud ice at 150 hPa: averages for 25 Aug through 6 Sep 2004. The MLS 200 and 600 GHz data allow separation of clouds into those with characteristic crystal sizes larger or smaller than ~30µm. **Bottom row**: GEOS-CHEM model of upper tropospheric CO and aerosol, and CMAP precipitation, for same period. Enhanced CO and aerosol over southern Asia are traced to convectively and orographically-lifted anthropogenic emissions from India and China. [M.J. Filipiak et al., and Q.B. Li et al., *GRL*, in press, 2005.]

CAMEO provides a needed new capability for determining the role of fast processes (e.g., deep convection) in linking regional pollution, global air quality and climate change. Quantifying biogenic emissions of VOCs is crucial for understanding tropospheric radical chemistry that affects air quality. Strong biogenic emissions of the VOC isoprene ($C_5H_8$) cause enhanced formaldehyde ($CH_2O$) to form over southeastern U.S. in summer, for example, as measured by UV/Vis technique from space and modeled as shown in Fig. 6. $CH_2O$ is an excellent proxy for VOC emissions. TROPI measures $CH_2O$ in the lower troposphere − aided by subtraction of SMLS upper tropospheric $CH_2O$ column. The TROPI observations of $CH_2O$, $NO_2$ and aerosol can be used in conjunction with inversions of chemical transport models to quantify these emissions. During summer, when VOC emissions peak, there is also frequent deep convection that deposits enhanced $CH_2O$ directly into the upper troposphere as shown in Fig. 6. This $CH_2O$ can be the primary source of $HO_x$ that regulates upper tropospheric $O_3$ production, especially in the tropics and subtropics. SMLS will, for the first time, quantify injections of $CH_2O$ and other boundary-layer gases into the upper troposphere, as well as the lower stratosphere. (UARS MLS detected $CH_3CN$, from a forest fire, injected into the lower stratosphere [Livesey et al., *JGR*, 2004].)

SMLS measures many upper tropospheric species, as shown in Fig. 7. Measurement of this suite of species, which exhibit a wide range of chemical lifetimes and solubilities, with the CAMEO temporal and spatial resolution will give a needed first 'climatology' of the extent to which the upper troposphere is directly affected by the boundary layer. The lower height limit of measurements is set by $H_2O$ and dry air 'continuum' attenuation. Radiance data from UARS MLS over a 5-year period indicate that SMLS typically will measure tropospheric trace species down to 9 km, $H_2O$ to 7 km, and temperature to 5 km. Measurements extend lower in dry situations; they generally can be made where $H_2O$ abundances are $<\sim1000$ ppmv.

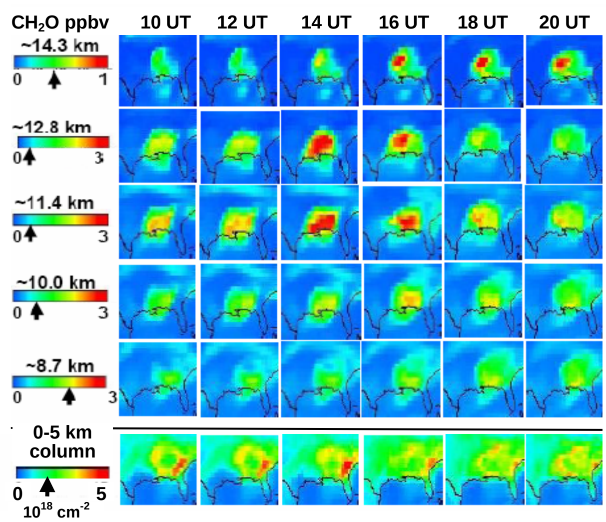



**Figure 6.** GEOS-CHEM results for $CH_2O$ over the southern U.S. on 11 July 2000. Convective deposition into the upper troposphere is seen at 14 UT. CAMEO has the same spatial and temporal resolution as this model. The CAMEO precisions are indicated by arrows on the color bars.

*Climate Variability and Change*

In addition to its importance for global air quality, quantifying the processes that affect upper tropospheric $O_3$ is crucial for reducing uncertainties in predictions of climate change. The increase in tropospheric $O_3$ since pre-industrial times is estimated [Prather, *IPCC*, 2001] to give the third-largest increase in direct radiative forcing of climate. It is in the upper troposphere that the effect of $O_3$ is largest. CAMEO provides information on the processes affecting upper tropospheric and lower stratospheric $O_3$ to a degree not previously possible, especially the fast convective processes that deposit boundary layer gases into the upper troposphere, where they can directly perturb $O_3$ chemistry. TROPI measurements of $CH_4$, an important greenhouse gas, also give information for climate change.

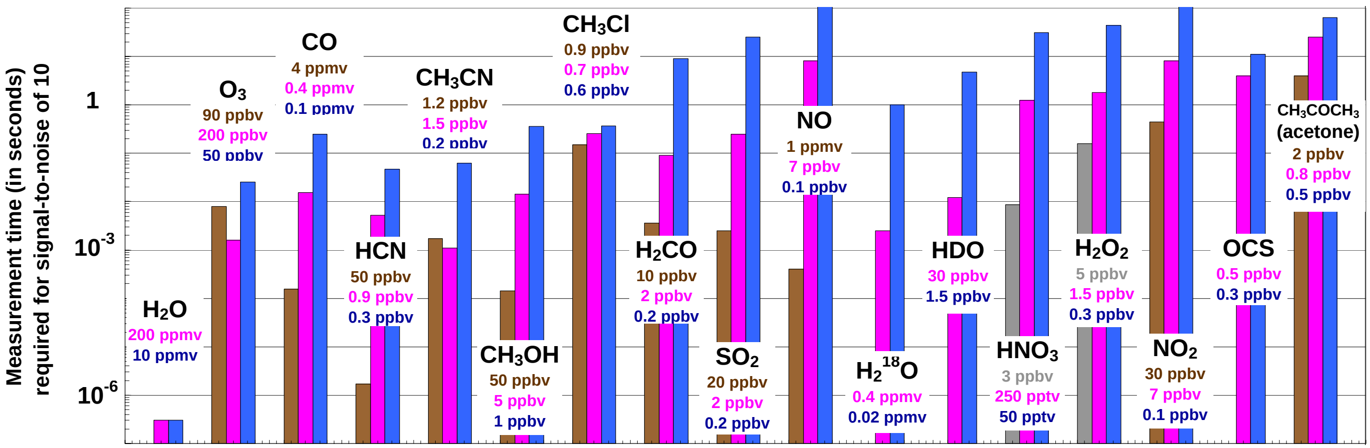



**Figure 7.** SMLS measurement time needed for an upper tropospheric spectral line radiance signal-to-noise of 10 for various species. The available measurement time depends upon the mode of the scan, which is programmable in both horizontal and vertical. A 'maximum global mode' with measurements at 20 points in the vertical and every 50x50 km in the horizontal over a 7700 km cross-track width allows 0.003 s for each individual measurement; a 'regional study mode' with, for example, measurements at 5 points in the vertical and every 50x50 km in the horizontal over a cross-track width of 2000 km allows 0.05 s for each measurement; a 'local study mode' with, for example, measurements at 3 points in the vertical and every 50x50 km in the horizontal over a 200 km cross-track width allows 1 s for each measurement. There is a 'continuum' of modes, easily implemented simply by programming the scan ranges. The available measurement time can be increased by degrading the spatial and/or temporal resolution: a factor of 4 increase, for example, is gained by changing from 50x50 km to 100x100 km horizontal resolution, which can be done in ground data processing. Because of the large dynamic range in many species abundances, useful measurements can be obtained with a signal-to-noise of 3, which reduces the required measurement time 9x from that shown here. The SMLS programmability allows it to easily respond to events and changing measurement priorities. Colors of the bars give representative abundances for different situations. Blue is for typical or minimum abundances; pink for enhanced abundances that have been observed or inferred; brown for enhanced boundary layer abundances that can be convectively transported to the upper troposphere; grey for soluble species that may reach the upper troposphere less easily. This plot is for a tropical 'background' atmosphere and 9 km height; it includes 2-3x attenuation of the target molecule signals by water vapor continuum, and spectral line wings of 'interfering' gases. For the tropical troposphere above 12 km, a region of considerable current interest, SMLS signals are typically 2-3x stronger than indicated here. All these measurements are made in the 180-280 GHz region, from spectral lines selected by considerations of (a) line strength, (b) freedom from interference, and (c) instrument simplification. Cloud ice measurements from 'continuum' emission, and temperature from $O^{18}O$, are obtained with good signal-to-noise in milliseconds.

The CAMEO suite of measurements and spatial/temporal resolution will diagnose how anthropogenic aerosols affect upper tropospheric cloudiness, a key question in regards to climate change and transport of $H_2O$ into the stratosphere. Fig. 5 shows MLS observations of correlations in enhanced upper tropospheric clouds and uplifted pollution. Has anthropogenic aerosol pollution contributed to the observed enhancement in clouds? This question is starting to be addressed with Aura data, but much better resolution microwave measurements, as provided by SMLS, are needed. Its ability to distinguish between 'large' and 'small' crystal clouds gives important diagnostics. The measurements of aerosol properties are essential for addressing pollution effects on clouds. Fig. 8 shows examples of aerosol measurements of the type TROPI will make several times daily over both land and sea. These measurements distinguish between reflecting and absorbing aerosols, as needed to improve climate models. The improved SMLS resolution, compared to MLS on Aura, greatly facilitates the combined analyses of microwave and UV/Vis/SWIR data.

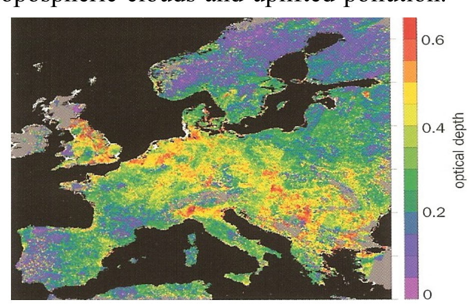
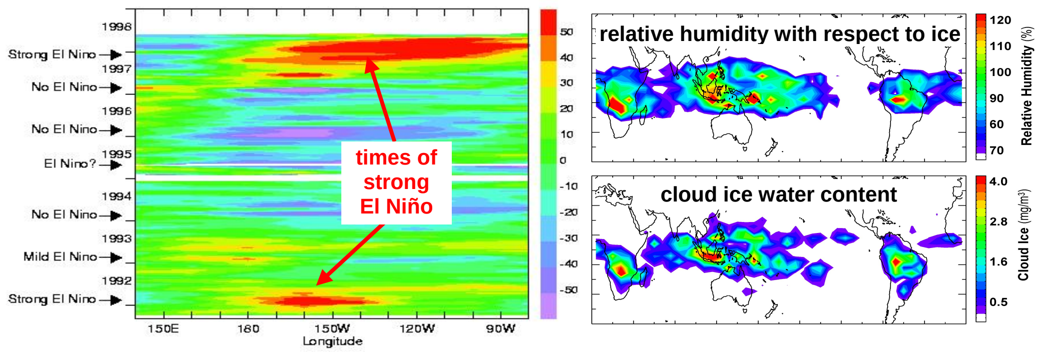



**Figure 8.** August 1997 monthly average aerosol [Gonzalez et al., *GRL*, 2000].

Our ability to predict climate variability is critically dependent upon accurately quantifying the processes that affect $H_2O$ in the upper troposphere. Upper tropospheric $H_2O$ can either amplify or attenuate the climatic effects of increases in other greenhouse gases, depending upon the process affecting it and the spatial and temporal scales of the process. Measurement of upper tropospheric $H_2O$ has historically been very difficult − due both to its relatively small abundance and to the presence of ice clouds that degrade or prevent its measurement by many techniques. Microwave limb sounding, however, is well-suited to this measurement because of its combination of good vertical resolution, sensitivity and long wavelengths that can measure both gas phase abundances in the presence of ice clouds and the larger ice amounts that saturate or block shorter wavelength techniques. (Scattering is inversely proportional to the 4$^{th}$ power of wavelength: small particles affect 1 mm wavelength microwaves $10^8$ times less than 10 μm infrared.) UARS MLS demonstrated the ability to measure upper tropospheric $H_2O$, and the left panel of Fig. 9 gives an example of results showing the effects of El Niño on upper tropospheric $H_2O$. The improved temporal and spatial resolution of SMLS on CAMEO, and its measurements of $H_2{}^{18}O$ and HDO (which yield additional information on condensation processes) – neither of which are available from Aura MLS – are needed to understand crucial details of processes affecting upper tropospheric $H_2O$ and its influence on climate variability.

**Figure 9. Left:** UARS MLS measurement of tropical Pacific upper tropospheric $H_2O$ anomalies (ppmv) showing El Niño effects [Waters et al., *JAS*, 1999]. **Right:** Aura MLS 150 hPa measurements of **(top)** relative humidity and **(bottom)** cloud ice water content: monthly averages for December 2004.




*Weather and Climate Modeling*

One of the most significant shortcomings in current weather and climate models is the representation of clouds and their feedbacks on the global water and energy cycles. This shortcoming includes both convective and non-convective clouds, applies to both GCMs and regional models, and impacts both weather and climate predictions. The accurate depiction of clouds and related hydrological processes in the upper troposphere is essential for predicting climate change. It is in the upper troposphere that water vapor feedbacks are most acute and cloud feedbacks – in this case from deep convective and high cirrus/ice clouds – are undeniably significant. Aura MLS has demonstrated simultaneous observations of cloud ice and relative humidity, as shown in Fig. 9, which are important for understanding cloud formation. The ability to produce height-resolved maps of cloud ice (as is the case for all SMLS measurements) is shown in Fig. 10. The bulk alignment of cirrus crystals has also been measured from polarization of the MLS signals [C. Davis et al., *GRL*, in review]. SMLS provides the improvements (see Fig. 2) over UARS and Aura MLS in temporal and horizontal resolution that are needed to understand the 'fast' convective processes affecting clouds and the hydrological cycle in the upper troposphere.

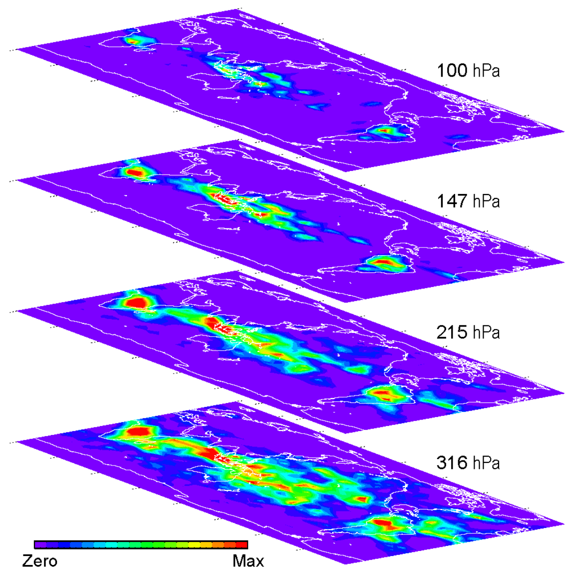



**Figure 10.** Ice in 4 upper tropospheric layers from Aura MLS: avg for Dec 2004. Colors give mg/m$^3$ ice water content: max is 1.2 @ 100 hPa, 4.5 @ 147 hPa, and 9 @ 215, 316 hPa.

Fig. 11 compares cloud ice from MLS, ECMWF analyses, and state-of-the-art GCMs. Considerable discrepancies in the amount and spatial variability of cloud ice are apparent in the GCM results. Reducing these uncertainties is crucial for improving both weather and seasonal climate (e.g., monsoon, ENSO) forecasts, and decreasing the uncertainties in long-term climate change. The MLS capability to provide these crucial measurements has been demonstrated, but better resolution is needed to fully exploit their impact on weather and climate models. CAMEO gives the needed improvement and produces unprecedented data for (1) model development and tuning, particularly in regards to cloud microphysical parameterizations, (2) augmenting initial conditions for weather forecasting, including rapidly evolving severe weather conditions, and (3) improving regional and global climate records through re-analysis.

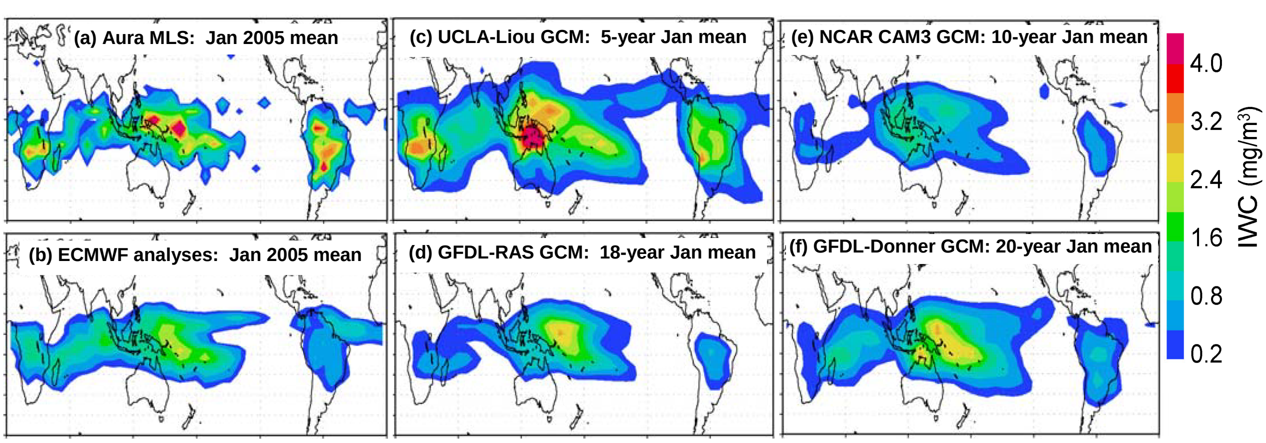



**Figure 11.** January mean cloud ice water content at 150 hPa for 2005 from (a) Aura MLS and (b) ECMWF analyses, and (c)-(f) multi-year GCM simulations. From J.F. Li et al., in preparation for *GRL*.

CAMEO provides a new resource for examining the diurnal cycle, another paramount shortcoming of weather and climate models. Fig. 12 shows the considerable GCM errors for both phase and magnitude of the precipitation diurnal cycle that – because it arises from a well-defined and strong external forcing – would be expected to be well-modeled. A number of current theories for the cloud and rainfall diurnal cycle explicitly involve upper tropospheric processes (e.g., Tian et al. *JGR*, 2004; 2005). CAMEO's high-frequency observations will provide sorely needed data for improving GCM performance in this area.

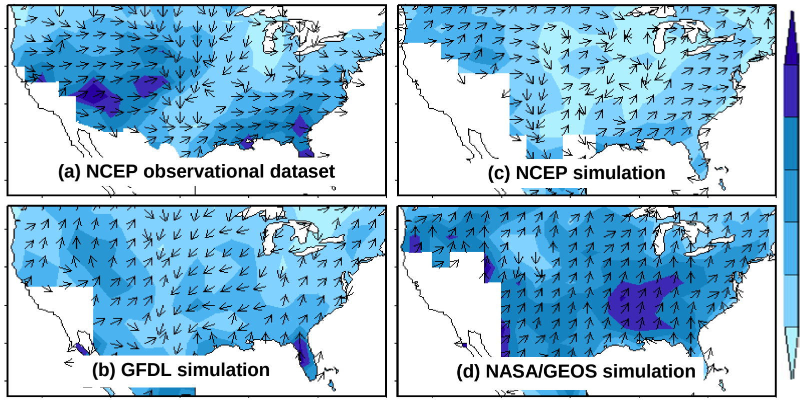



**Figure 12**. Comparing observed and modeled diurnal cycle of Jun-Jul-Aug precipitation (from M.I. Lee et al., in preparation for *J. Climate*). Blue shading is the normalized percentage amplitude (the mean diurnal amplitude relative to the 24-hour mean); the arrows indicate the local time (LST) of maximum (south-pointing ⇒ 00 LST, west ⇒ 06, north ⇒ 12, and east ⇒ 18 LST). (a) NCEP Hourly Precipitation Dataset (HPD) for years 1983-2002. Panels (b), (c), (d) are GFDL, NCEP and NASA/GEOS five-member ensemble simulations. Areas having more than 0.1 mm/day precipitation are shown.

An especially important area of uncertainty is northern high-latitude climate change. Evidence from limited observations and aggregate results of GCM simulations indicates that anthropogenic climate changes will be largest and most readily-observed at high northern latitudes (e.g., Hartmann et al., *Proc. NAS*, 2000). This inference, however, must be considered with caution as the predictions are based on GCMs that exhibit considerable differences/errors in their representation of northern high-latitude climate. There are difficulties in simulating the observed high latitude surface warming (Moritz et al., *Science*, 2002), regional water recycling, dehydration processes, snow/precipitation, snow-albedo feedback (Walsh et al., *J. Climate*, 2002), and principal modes of circulation (e.g., Shindell et al., *Nature*, 1999; Moritz et al., *Science*, 2002). Reconciling these differences and addressing model shortcomings require observations with improved spatial and temporal resolution for processes influencing high-latitude water and energy cycles. Previous satellite observations of clouds have been notoriously poor over high latitudes, especially during winter (Wyser and Jones, *JGR*, in press, 2005), primarily due to reliance on visible and infrared wavelengths and nadir-viewing geometry. The SMLS vertical, horizontal and temporal sampling – and its ability to sound deep into the atmosphere at these latitudes because of the dry air – gives new information on high-latitude processes needed for model improvements.

SMLS capability for gravity wave observations is greatly improved over that of previous MLS instruments (e.g., Wu and Zhang, *JGR*, 2004). Its resolution of large-amplitude fast-propagating gravity waves, for example, will help improve parameterizations of these waves – needed to accurately model atmospheric circulation and thermal structure.

*Ozone layer stability*

Efforts over the past 3 decades by scientists, government and industry are rightfully recognized as tremendously successful in regards to safeguarding our ozone layer without damaging our economy. However, we should not let this success lead to complacency – and remember that the threads leading to discovery of the CFC threat to ozone were tenuous: Lovelock's curiosity in using his new electron capture detector for measuring CFCs on a British ship bound for the Antarctic; the fortuity of his presenting the results at a conference attended by Rowland; Rowland and Molina's curiosity in pondering the ultimate fate of CFCs released into the atmosphere. Even after 10 years of intense research to understand chlorine destruction of stratospheric $O_3$, its most spectacular manifestation – the Antarctic ozone hole discovered through Farman's careful measurements and analyses – completely shocked the community of scientists working this issue. Although CFC production has been curtailed, the stratosphere will be loaded with chlorine for at least the next few decades. As stratospheric $O_3$ can be destroyed through many catalytic cycles influenced by human activity, we should not take the stability of the ozone layer for granted. The historical examples mentioned here teach us the necessity of continuing careful measurements.

CAMEO provides the needed critical measurements to monitor ozone layer stability and give early warnings of changes. In addition to $O_3$ itself, SMLS measures both the dominant chlorine reservoir (HCl) and reactive radical (ClO) involved in stratospheric $O_3$ depletion, which give crucial information on whether chlorine partitioning is changing with changing climate (e.g., a cooler stratosphere would cause more chlorine to be in the $O_3$-destroying ClO form). SMLS measurements of temperature, $HNO_3$, $H_2O$, ClO, HCl (and possibly TROPI measurements of aerosol extinction by thick polar stratospheric clouds) provide additional information on microphysical processes that can trigger increased $O_3$ destruction. Fig. 13 shows Aura MLS measurements made with coarse resolution. The better SMLS resolution, and temperature precision of 0.1 K, provide needed new insights into these complicated and extremely temperature-dependent processes. The long-lived tracers $N_2O$, CO (and, in many situations, $H_2O$ and $O_3$) give information on dynamics and transport. These, along with temperature, diagnose tropopause structure and other dynamical effects that strongly

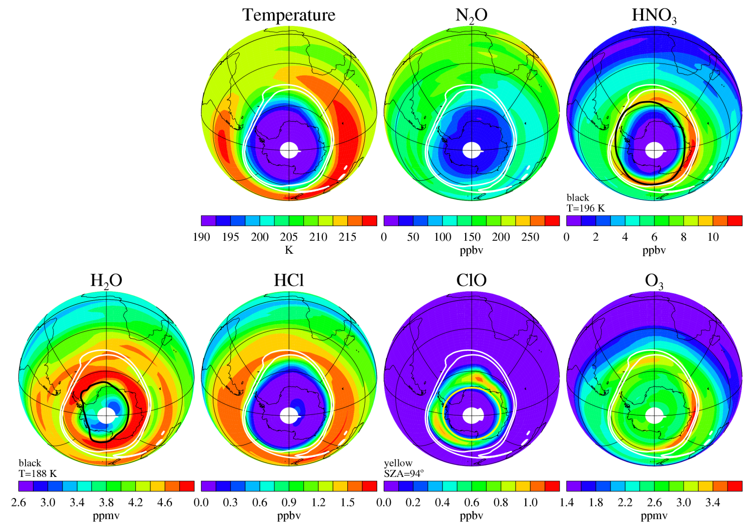



**Figure 13.** Measurements related to ozone layer stability made 3 Aug 2004 by MLS on Aura. These are for an isentropic layer at ~18 km (lower stratosphere). Two potential vorticity contours (white) show the edge of the Antarctic vortex. Vortex temperatures are very low; $N_2O$ is also low due to descent. The descending air also brings high values of $HNO_3$ and $H_2O$. In the coldest regions, $HNO_3$ and $H_2O$ are depleted by formation of polar stratospheric clouds. Reactions on these clouds convert chlorine from the reservoir HCl to $O_3$-destroying ClO. The yellow contour on the ClO map (showing only day side of the orbit) indicates the edge of daylight, which is required for large abundances of ClO. The sun is just returning to the Antarctic at this time of year, and the ozone hole is just starting to develop. Santee et al., and Manney et al., [*GRL*, in press, 2005] give more information.

influence column ozone. The high-resolution SMLS data will enable progress in stratospheric and upper tropospheric dynamics that was planned for Aura but lost due to a HIRDLS mishap. Their new temporal resolution, in addition, will help quantify the extent to which fast convective processes might be transporting short-lived ozone-depleting substances into the stratosphere. HCl in the upper stratosphere is a measure of total chlorine loading and thus a crucial test of international regulations to reduce stratospheric chlorine; CAMEO continues the long-term global HCl measurements from UARS and Aura. BrO is both the dominant form of bromine in the stratosphere and the dominant form of bromine that destroys $O_3$. There are still regulatory issues regarding certain bromine compounds, and the BrO measurement provides information needed for policy decisions balancing economic and environmental concerns. $H_2O$, $HO_2$, and $H_2O_2$ monitor hydrogen chemistry, and $N_2O$, $HNO_3$, $NO_2$, and NO monitor nitrogen chemistry – both important for tracking ozone layer stability. The very broad spectral programmability of SMLS (section 4h) gives a capability for measuring additional gases should the need arise. The SMLS ability to measure trace gases in dense volcanic aerosol, demonstrated on UARS following the Pinatubo eruption, is key to quantifying the effects of volcanic eruptions on the ozone layer. TROPI continues the very accurate long-term and high-resolution measurements of column ozone.

### 4d. Contributes to applications and policy making

CAMEO contributes to policy making with important new data on global emissions affecting air quality, the transport of pollution, and processes affecting climate. It gives crucial data for continually assessing policy on ozone-depleting substances. OMI data already have planned use in several applications, including (1) surface UV-B forecasts, (2) air quality forecasts, (3) volcanic plume monitoring for aviation control, and (4) improving mid-range weather forecasts using ozone column and profile data. Data from TROPI have similar applications. CAMEO's high spatial and temporal resolution measurements of $O_3$, CO, $NO_2$, $H_2CO$, and aerosols can be assimilated into models such as the EPA regional air quality models CMAQ/Model 3 to improve air quality forecasts. Its measurements of upper tropospheric water and clouds can be used for augmenting initial conditions for weather forecasting, including rapidly evolving severe weather. Appropriate near real time data products will be produced from CAMEO for these applications.

### 4e. Contributes to long-term monitoring of Earth

CAMEO will continue the important global data records for processes affecting ozone layer stability, upper tropospheric water vapor and ice affecting climate, and gases affecting air quality. Long-term monitoring of these is essential for understanding global change and improving its prediction. The CAMEO measurement techniques have demonstrated the long-term calibration stability required for such measurements. Data from UARS MLS, for example, indicate that its calibration changed by less than 0.02% over 5 years [Waters, et al., *IEEE GRS* Aura special issue, 2005].

### 4f. Complements other observational systems

CAMEO complements other systems with a new combination of resolution, global coverage, and upper tropospheric measurements. Its measurements can be combined with other measurements to increase the overall aggregate value − assimilation (including direct assimilation of radiances that may be viable by the time of CAMEO) being a particularly powerful method. Use of Aura OMI and MLS data has already yielded improvements in NASA GMAO assimilation output products. MLS data have been tested in the ECMWF assimilation system, and demonstrated a potentially significant and useful impact. OMI data are planned to be assimilated by ECMWF and possibly NOAA-NESDIS.

### 4g. Affordable (cost-benefit)

With just two instruments and an easily-reached orbit, CAMEO provides needed new information on the health of our planet and our ability to predict changes, and continues critical measurements for assessing ozone layer stability. We believe that its benefits are well worth its cost. Excellent opportunities exist for international cost-sharing.

## 4h. Degree of readiness

*Scanning Microwave Limb Sounder*

The SMLS concept has been under development at JPL for several years. It combines (a) ultra-sensitive SIS (superconductor-insulator-superconductor) radiometers, versions of which have been used for atmospheric measurements for 20 years, and are now in the Japanese SMILES stratospheric instrument planned for the Space Station and (with JPL SIS devices) in the HIFI instrument for the European Herschel astrophysics mission, and (b) a new antenna whose principle has been demonstrated by functional models, with geometric and physical optics designs performed for SMLS. Flight-qualified coolers, required for the SIS devices, are in the SMILES instrument and the European Planck astrophysics mission. U.S. industrial sources exist for the SMLS cooler, similar to those being developed for the James Webb Space Telescope. The SMLS design requires <180 W, including all inefficiencies, for the cooler drive power.

SMLS uses advanced SIS radiometers that cover >100 GHz bandwidth, recently demonstrated by Caltech for radio astronomy. These give useful atmospheric measurements with only milliseconds of measurement time (see Fig. 7). SMLS has radiometers covering two broad bands: 180-280 GHz (both polarizations) mainly for the troposphere, and 580-680 GHz mainly for the stratosphere. (SMLS has 3 radiometers, compared to 7 for MLS on Aura.) The National Radio Astronomy Observatory is implementing an array of 200 SIS sideband-separating radiometers, as used by SMLS, around 230 GHz with sensitivity 2× better than required for SMLS.

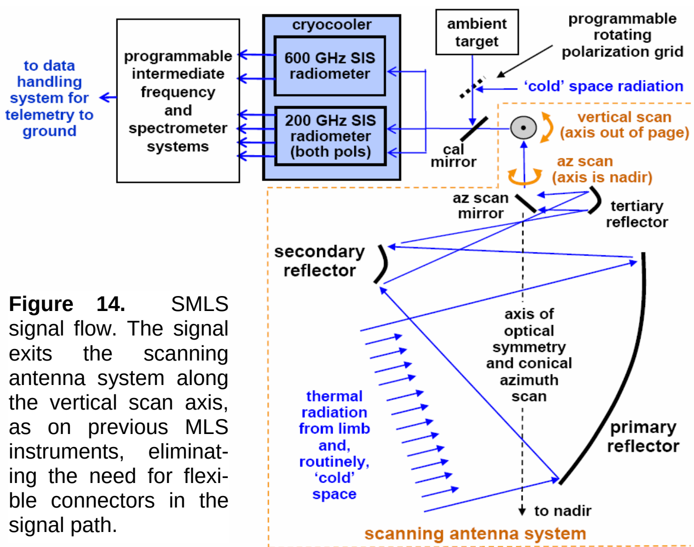



**Figure 14.** SMLS signal flow. The signal exits the scanning antenna system along the vertical scan axis, as on previous MLS instruments, eliminating the need for flexible connectors in the signal path.

Fig. 14 shows the SMLS signal flow. Limb radiation is collected by a 4m × 2m primary reflector. The antenna is scanned in the vertical, as on UARS and Aura MLS, by ~1$^o$ rotation. For SMLS a vertical scan is performed every 10 s to give along-track sampling of 50 km, the orbital movement of the measurement track in 10 s. The conical azimuth limb scan is repeated every 0.5 s during the vertical scan by rotating back and forth a 10-cm mirror. The ±65$^o$ azimuth scan range enables a 7700 km cross-track swath from the 1500-km CAMEO orbit. A measurement is made every 3 ms to give 50 km cross-track sampling that matches the along-track sampling. 'Overscan' in the vertical accounts for Earth's oblateness and changes in vertical scan range with azimuth. A multipoint calibration is performed between each azimuth scan. All mechanisms have 5-year (or longer) operational lifetime.

Both the azimuth and vertical scans are programmable – as is the measurement suite, which is selected by tuning local oscillators. One set of measurements is made continuously (e.g., $H_2O$, cloud ice, temperature, $O_3$, CO); other sets of related measurements are time-shared to reduce the required number of spectrometers. Time-sharing modes can be changed as often as each vertical scan. The programmability and spectral coverage allow measurements of new species: in principle, nearly any species with a dipole moment. Spectral surveys will be performed to test, within the limits of the SMLS sensitivity and spectral ranges, the completeness of our knowledge of atmospheric composition.

All the SMLS technologies have been flight-qualified. Development of key SMLS components is ongoing through internal JPL funding. Major needs for developing the satellite instrument are (a) studies to get better estimates of mass, power, the configuration envelope, number and type of spectrometers, etc., and (b) development of an instrument that could be used from mountaintop to determine practical limitations for the new tropospheric measurements.

SMLS power consumption is 400 W (150 W less than Aura MLS), its mass is 450 kg (same as Aura MLS), and its data rate is 5 Mb/s. The needed personnel are available at JPL to implement SMLS. It can be ready for launch in 2011.

*Tropospheric Pollution Imager*

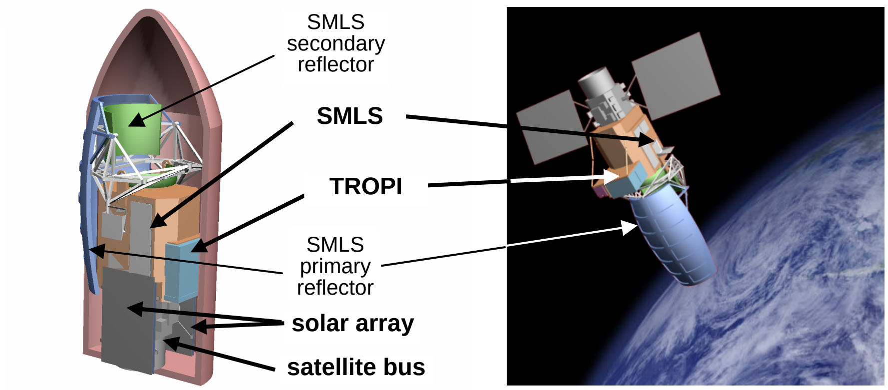
TROPI development, using two-dimensional detectors based on the OMI design, started 1.5 years ago in the Netherlands. It also uses other developments from both OMI and SCIAMACHY. TROPI measures from 300 nm (or 270 nm, currently under investigation) to 800 nm in the ultraviolet/visible, and in a narrow range around 2.3 μm in the short-wavelength infrared. The UV/Vis portion measures $O_3$, $NO_2$, $CH_2O$, $SO_2$, BrO and $H_2O$; aerosol optical thickness with identification of selected aerosol types; cloud fraction and thickness; and surface UV-B flux. The SWIR portion measures CO and $CH_4$. The overall instrument requirements are set to quantify surface emissions of $NO_2$, CO, $CH_4$, $SO_2$, VOCs (through the $CH_2O$ proxy discussed earlier), and aerosol properties.

Two-dimensional detector arrays are used, with one axis of the array giving spectral information and the other giving cross-track spatial information. The UV/Vis swath width is 4700 km, and the SWIR swath width is 2000 km; the design gives 20×20 km spatial resolution from the CAMEO orbit. The power consumption is 300 W, mass is 250 kg, and data rate is 5 Mb/s. TROPI can be ready for launch in 2011.

*Launch vehicle, satellite bus, and operations*

CAMEO can be inserted directly into the desired mid-Earth orbit by a two-stage Delta-II rocket. The radiation environment of this orbit does not stress the mission or instrument designs. Fig. 15 shows the configuration of CAMEO with both instruments on a single satellite bus (1) stowed for launch and (2) deployed in orbit. CAMEO can also be implemented with the two instruments on separate satellites flying in formation. A small commercial satellite bus (e.g., Spectrum Astro or Ball) could be used for a mission with SMLS and another small instrument. CAMEO operations can be similar to those of Aura, with central mission operations and remote science teams doing instrument operations. CAMEO does a yaw maneuver 8 times per year to keep its 'cold side' (containing radiators) away from direct sunlight. The yaw maneuver is straightforward to implement, and does not degrade measurement coverage because the instruments have symmetric measurement swaths on both sides of the orbit track. A 5-year design lifetime (for measurement of interannual variability) and a launch date of 2011 (in anticipation of some overlap with Aura) are proposed. It is anticipated that an 'SMLS science steering group' (interested leaders in atmospheric science or their delegates), will be formed to help set prioritized objectives for the programmable SMLS measurements.

**Figure 15.** Conceptual drawings of CAMEO **(left)** stowed in the faring of a Delta-II rocket and **(right)** deployed in orbit showing SMLS looking into the page. The SMLS primary reflector is stowed and deployed using a precision hinge and latching mechanism, such as developed by NASA'S LaRC for the James Webb Space Telescope, that has the needed accuracy and precision.




## 4i. Risk mitigation and strategic redundancy

SMLS risk can be mitigated by developing a demonstration instrument for mountaintop measurements. (Demonstration of useful mountaintop measurements could allow considerations for deployment of instruments on skyscrapers, as an adjunct to the satellite measurements, for detailed observations over urban areas. An aircraft instrument would be a valuable research and validation tool.) SMLS has identical 180-280 GHz radiometers at orthogonal polarizations, which provide redundancy for upper tropospheric measurements. There is redundancy in some stratospheric measurements, including re-programming some to the 180-280 GHz radiometers (but with reduced measurement quality). The scan and cooler electronics have redundancy.

## 4j. Fits with other national and international plans and activities

CAMEO can provide demonstration of important new candidate instruments for NOAA's post-GOES-R operational system (NGOESS) planned for MEO. A 5-year CAMEO mission starting around 2011 would provide the needed demonstration for confident implementation of their capabilities in NGOESS. CAMEO's objectives are in line with those of a recent ESA AO, to which the Dutch authors are proposing TROPI. CAMEO gives an excellent opportunity to implement the international cooperation advocated by the Earth Observation Summit held July 2003 in Washington, D.C.

## 4k. Data management and processing plan

Data processing and validation are expected to be the responsibility of the instrument science teams, as done successfully for Aura's MLS and OMI by the teams proposing the CAMEO mission concept.

A two-tier processing scheme is envisaged for SMLS. The first is routine continuous production of a 'spatial low-resolution' dataset (maybe 500×500 km horizontal as was planned for HIRDLS on Aura) with full temporal resolution. This contains geophysical parameters that are produced using a combination of optimal estimation and, for some products, more approximate but faster methods such as neural-networks. It will be made publicly available either through a central facility or through an extension of the Science Investigator-led data Processing System (SIPS) arrangement now used for Aura. The second tier is production of high-resolution 'regional' datasets generated with full optimal estimation algorithms as used for MLS on Aura. A concept will be explored whereby portable 'regional' software is made available for data processing by 'regional' users; this can reduce computational requirements on a central facility. An SMLS near real time capability for operational applications will be implemented. We anticipate the U.K. University of Edinburgh contributing to the SMLS data processing algorithms and validation, as done for previous MLS experiments.

The TROPI algorithms will be based on algorithms used for previous instruments such as OMI. OMI data sets are produced by the SIPS at NASA GSFC and the fully SIPS-compliant facility at KNMI in the Netherlands. An OMI near real time facility is under development to provide data for weather forecasts, smog forecasts, UV-B forecasts and volcanic plume data for aviation control. Similar products are envisaged for TROPI on CAMEO.